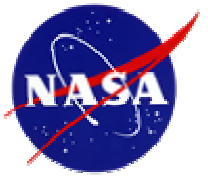
LEWICE 2.2 Capabilities and Validation

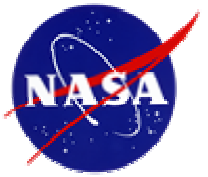
William B. Wright
QSS Group, Inc.

Aug. 22, 2002



Outline

- Background
- Bleed Air Capabilities
- External Review
- Heat Transfer Correlations
- Validation Tasks



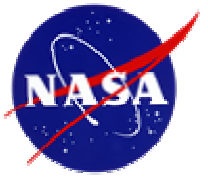
LEWICE

- **Flow Solver**
  - Use potential panel code to determine flow field about clean surface
- **Droplet Trajectories**
  - Calculate water droplet trajectories from some upstream location until impact on the surface or until body is bypassed
- **Water Collection**
  - Determine water droplet impact location pattern between impingement limits
- **Heat Transfer**
  - Perform quasi-steady analysis of control volume mass and energy balance in time stepping routine
- **Ice Growth**
  - Density correlations used to convert ice growth mass into volume
- **Iterate**
  - With new ice shape, iterate entire routine

LEWICE/Thermal

Thermal Ice Protection System Simulation

- **Approach**
  - Used LEWICE model for flow field and trajectories
  - 2D unsteady heat transfer model
- **Features**
  - Composite body structure
  - Individual heater sequence with different power to each heater
  - Gaps between heaters
  - Predicts ice accretion, shedding, melting, and refreezing
  - Water runback on surface using the LEWICE model



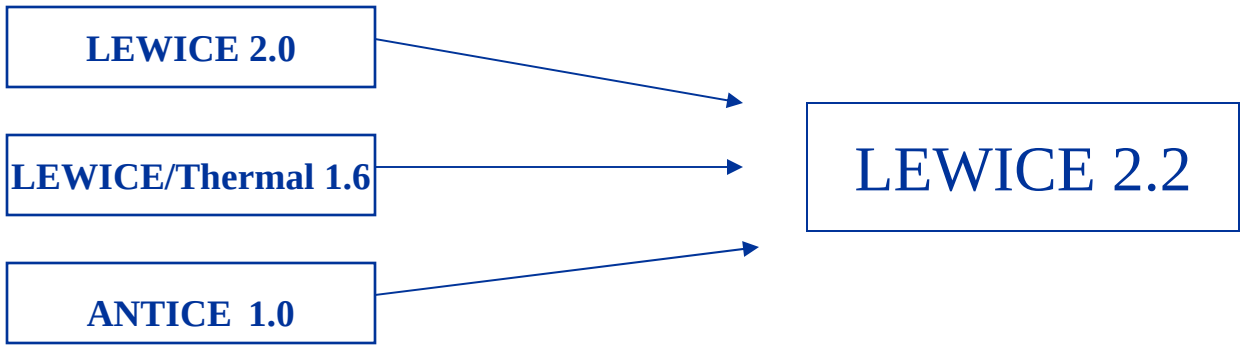
ANTICE

Thermal Anti-Icing Simulation

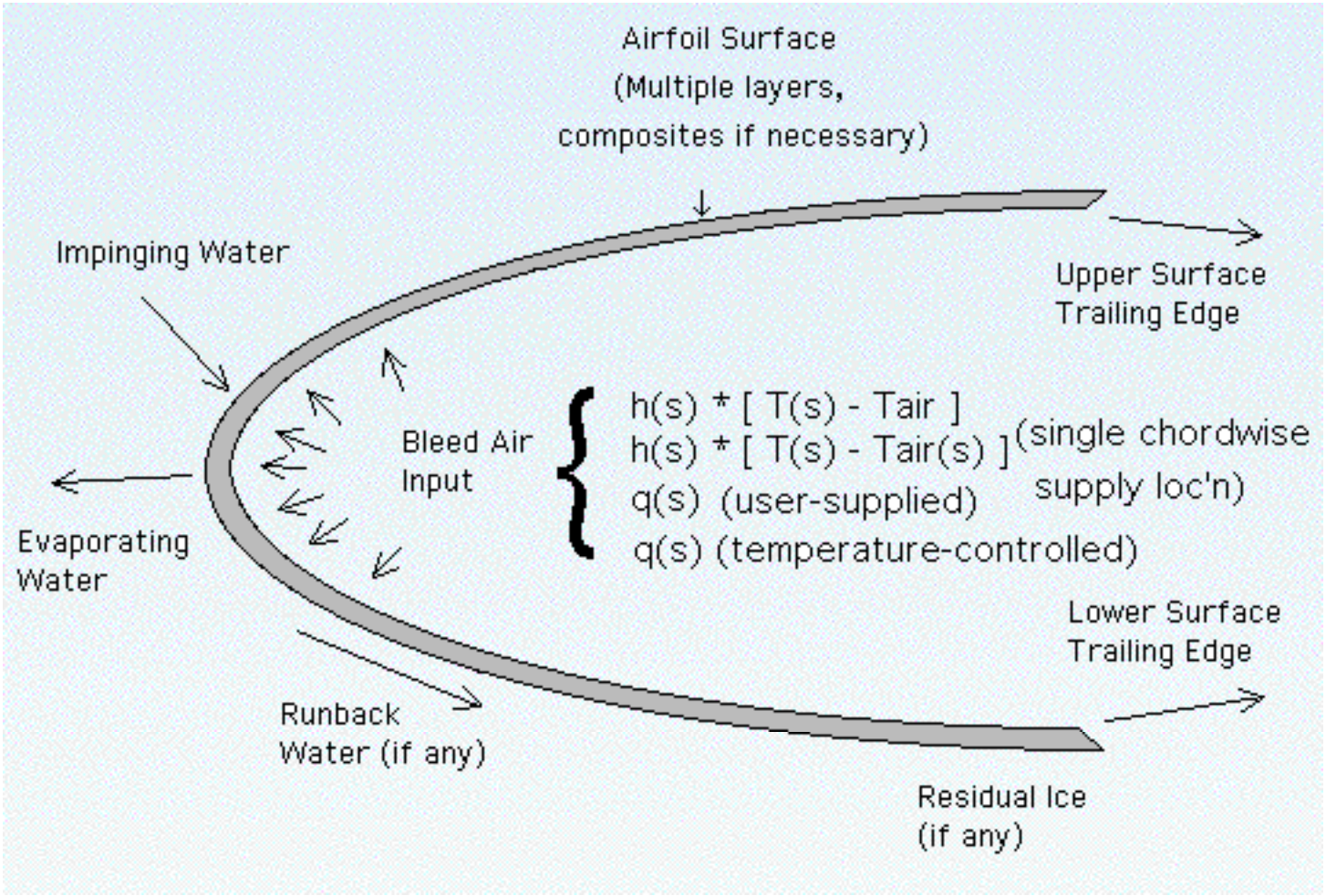
- **Approach**
  - Flow and trajectory solutions required from other sources
  - 2D steady heat transfer model
- **Features**
  - Composite body
  - Multi-zone electro-thermal heaters with different power densities
  - Gaps between heaters
  - Hot gas anti-icing system (streamwise gas flow)
  - Specified surface heat flux distribution
  - Surface water runback and surface wetness factor (rivulet model)
  - Partial and full evaporation, and freezing

LEWICE 2.2

- **Combines features of LEWICE, LEWICE/Thermal and ANTICE**
  - **Multi-time step**
  - **De-icing or Anti-icing**
  - **Electrothermal or hot air**
  - **Uses results from other sources**
- **Added features**
  - **Optimized heater sequencing**
  - **Multiple boundary conditions for bleed air analysis**



Bleed Air Capabilities



Bleed Air Boundary Conditions

- Convective HTC user-supplied
  - Constant bulk temperature in bleed air (multiple supply locations)
  - Variable bulk temperature in bleed air (user-supplied input location)
- Inner surface heat flux user-supplied
- Inner surface heat flux controlled by temperature

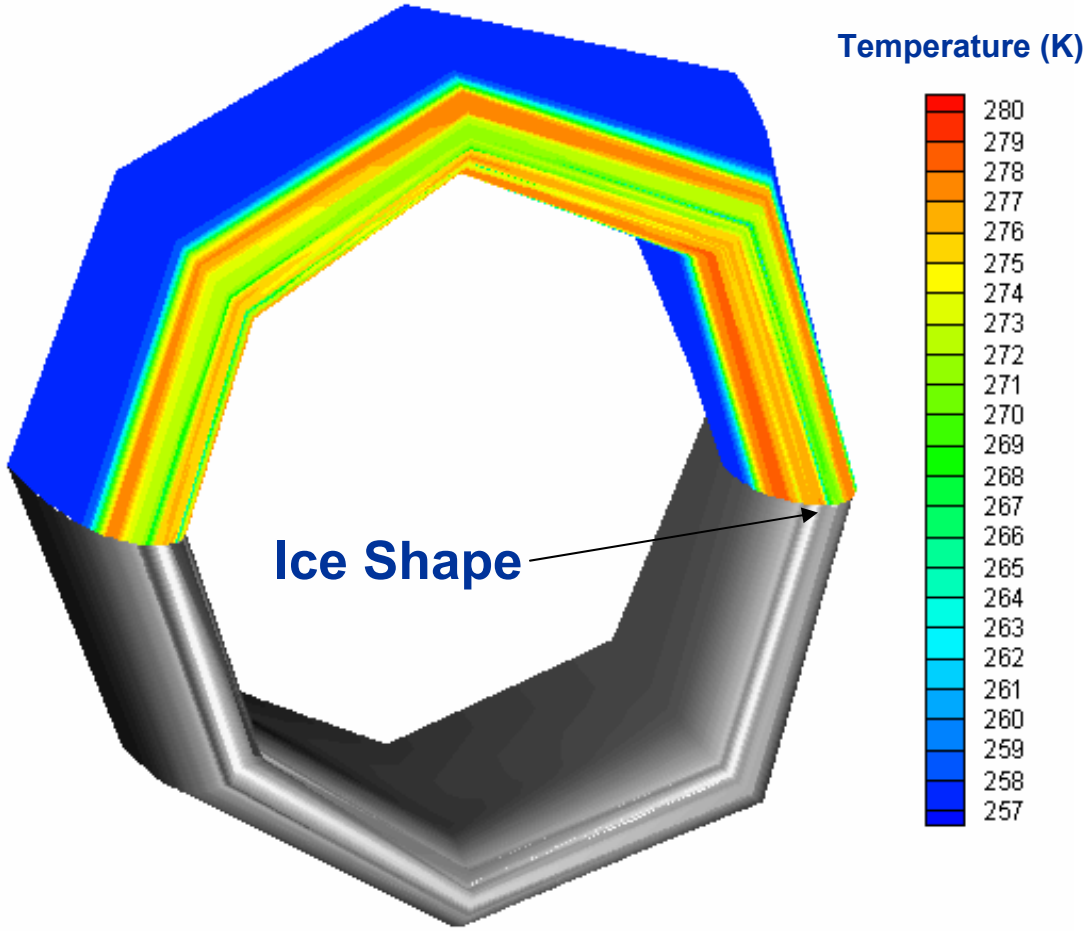
- All should be capable of modeling piccolo tube design
  - Multiple methods provided for user convenience

- Requires separate method to translate design criteria (hole size, spacing, mass flow rate, etc.) into required input

Bleed Air Test Case

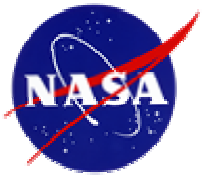
- Half-Model Symmetric Engine Inlet
- LEWICE 3D Example Case
- 5 Thermal Runs Obtained on Each 2D Streamline
- Bleed Air Flow Rate Reduced To Obtain Runback for Illustration
- V = 150 kts, LWC = 0.2 g/m^3, MVD = 20 μm, T = 0°F, t = 3 min

Bleed Air Test Case



External Reviews

- Academic Review
  - Software verification
  - Grid sensitivity
  - Time-step sensitivity
- Industry Review
  - Applicability to piccolo tube systems
  - Usability of software
  - Accuracy of results
    - 18%-30% lower than experiment



Review Recommendations

- Change data inputs
  - Inputs should be d, T, P, z_n, c_n rather than htc or q arrays
- Include surface temperature array as input
  - Useful for calibration
- Develop experimental database
- Use a fixed reference point for wrap distance
- Implement a fixed transition point for b.l.
- Fix two program errors “bugs”
  - Dual heat flux b.c.
  - Large anisotropic ratios

Changes Due to Review

- Included all suggested user options
- Fixed program errors
- Added correlations for piccolo heat transfer

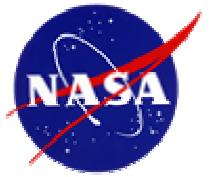
$$\overline{Nu} = C * \mathrm{Pr}^{1/3} * \mathrm{Re}^{a} * \left(\frac{z_n}{d}\right)^{b} * \left(\frac{c_n}{d}\right)^{e}$$

  - Variation in powers from literature
  - C= 0.453, a= 0.691, b= -0.22, e= -0.38 (Tawfek) $6 \le z_n/d \le 58$
  - C= 0.251, a= 0.68, b = 0.15, e = -0.38 (Gau & Chung) $2 \le z_n/d \le 8$
  - C= 0.394, a= 0.68, b = -0.32, e = -0.38 (Gau & Chung) $8 \le z_n/d \le 16$

$$\overline{Nu} = \mathrm{Re}^{0.76} * \left[\frac{24 - \left|\frac{z_n}{d} - 7.75\right|}{533 + 44 * \left(\frac{c_n}{d}\right)^{1.394}}\right] \qquad \text{(Goldstein et. al.)}$$

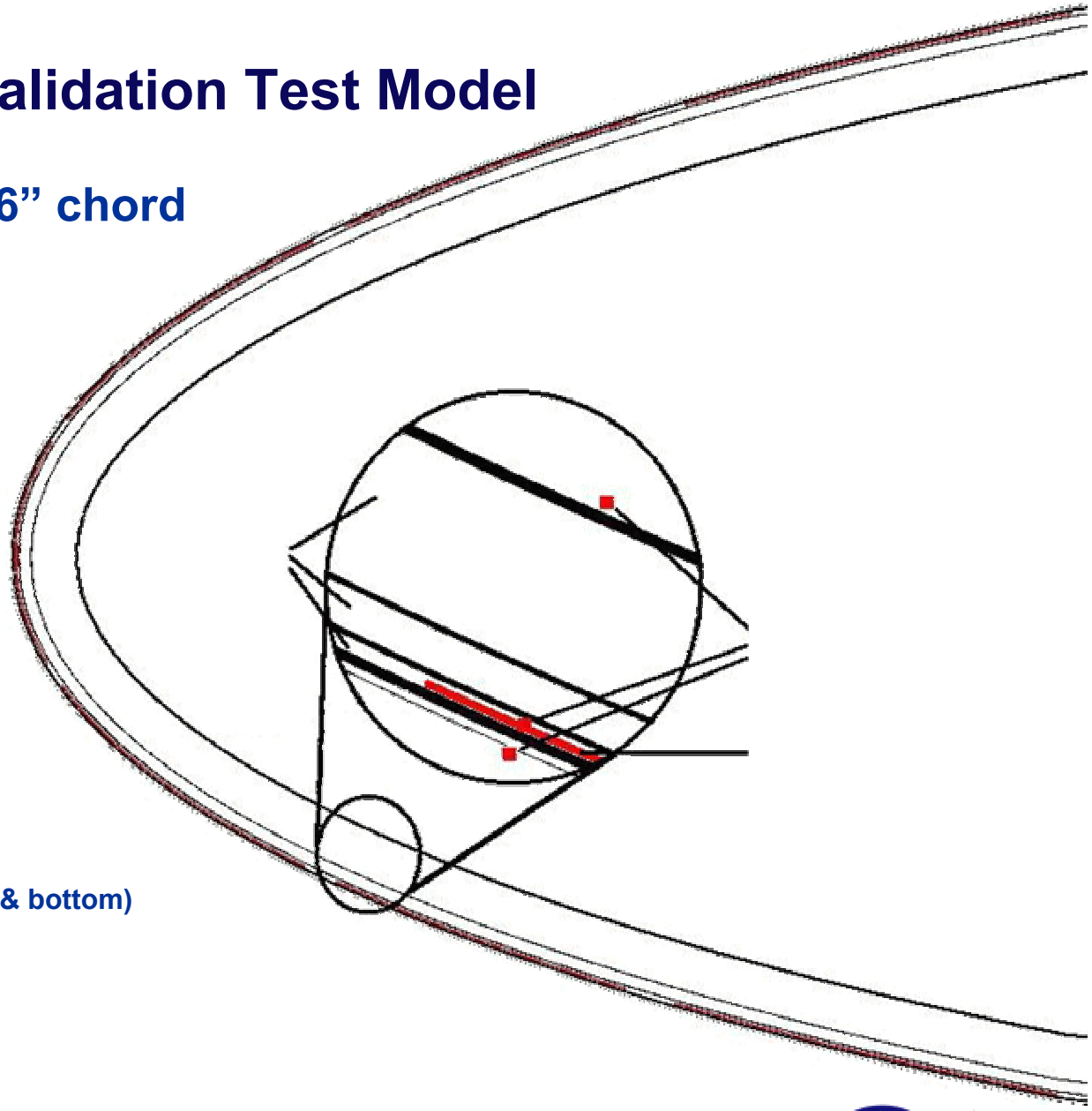
Electrothermal Validation

- Two week entry in 1996
- NACA0012 airfoil
- Electrothermal heater designed by Cox & Co.
- 100+ cases
  - 12 tunnel conditions
  - De-icing and anti-icing runs for each condition

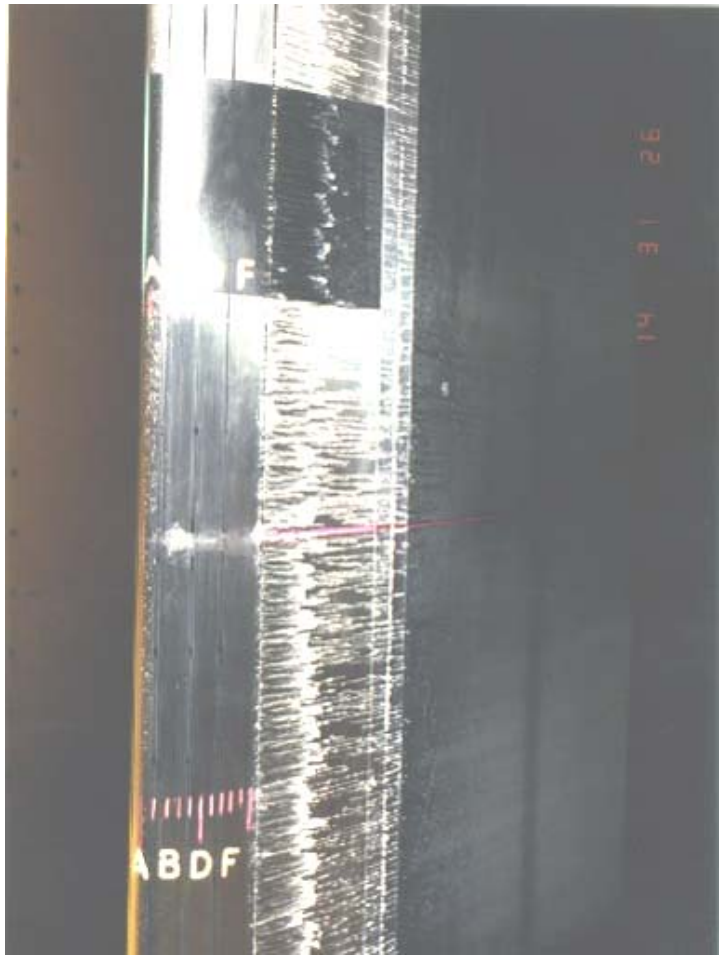


Validation Test Model

- NACA0012 airfoil, 36” chord
  Mounted vertically
- 7 Heaters
- 3 Operative Modes
  - Running Wet
  - Evaporative
  - De-icing
- Data Acquisition
  - Photos
  - Video
    - Standard VCR
    - BetaCam
    - InfraRed
  - 42 Thermocouples
    - 3 per heater location
    - 2 sets of heaters (top & bottom)

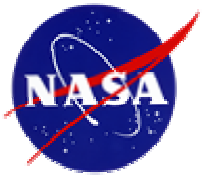


Run22 Anti-Icing Case

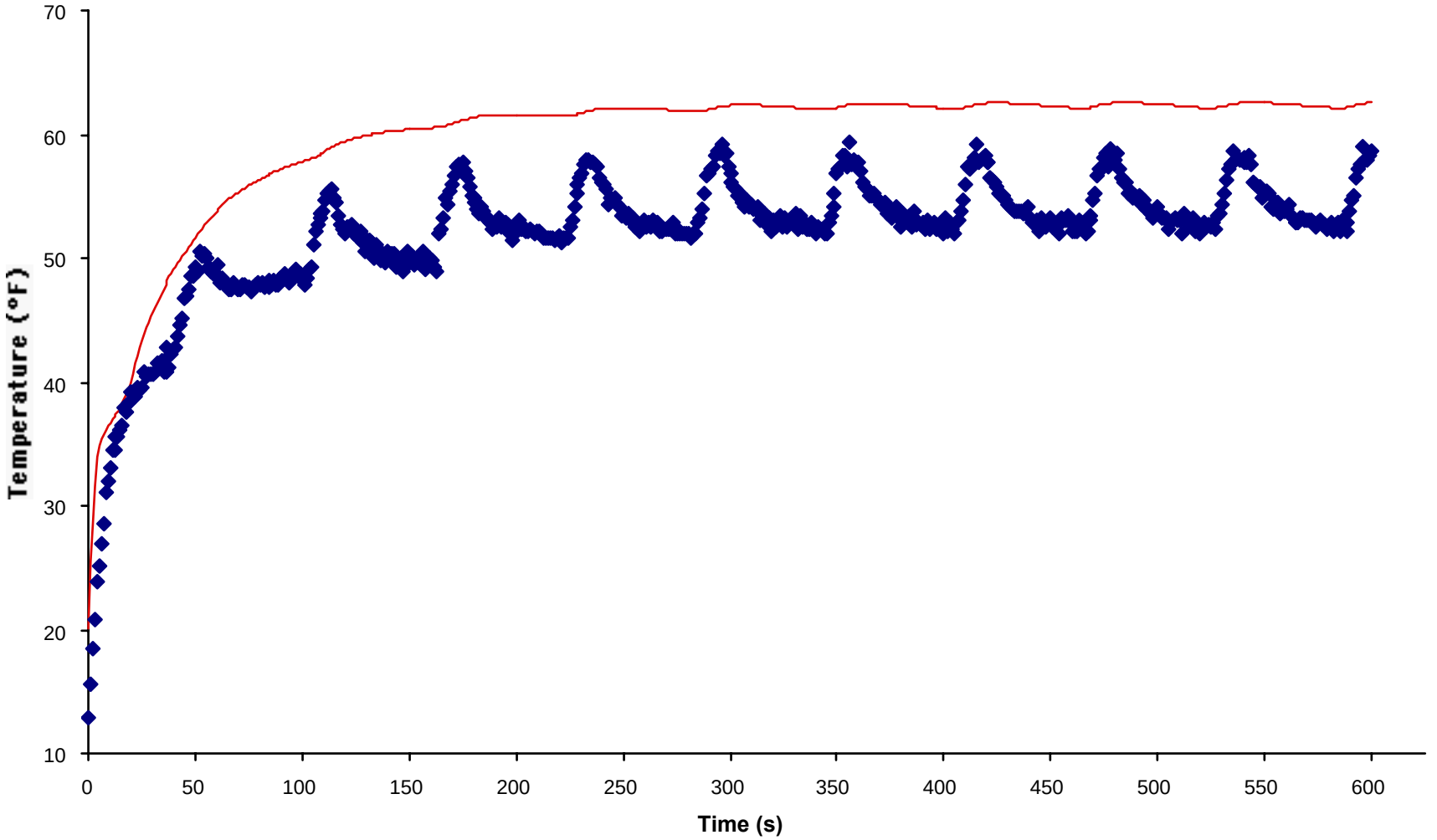


Electrothermal Validation Tasks

- Coordinate experimental data
- Run cases
- Parametric studies
  - Power variations
  - Material property/thickness variations
  - Grid density (more points/time steps)
- Compare data
  - Percent error
  - Absolute error
  - Comparison plots
- Validation report

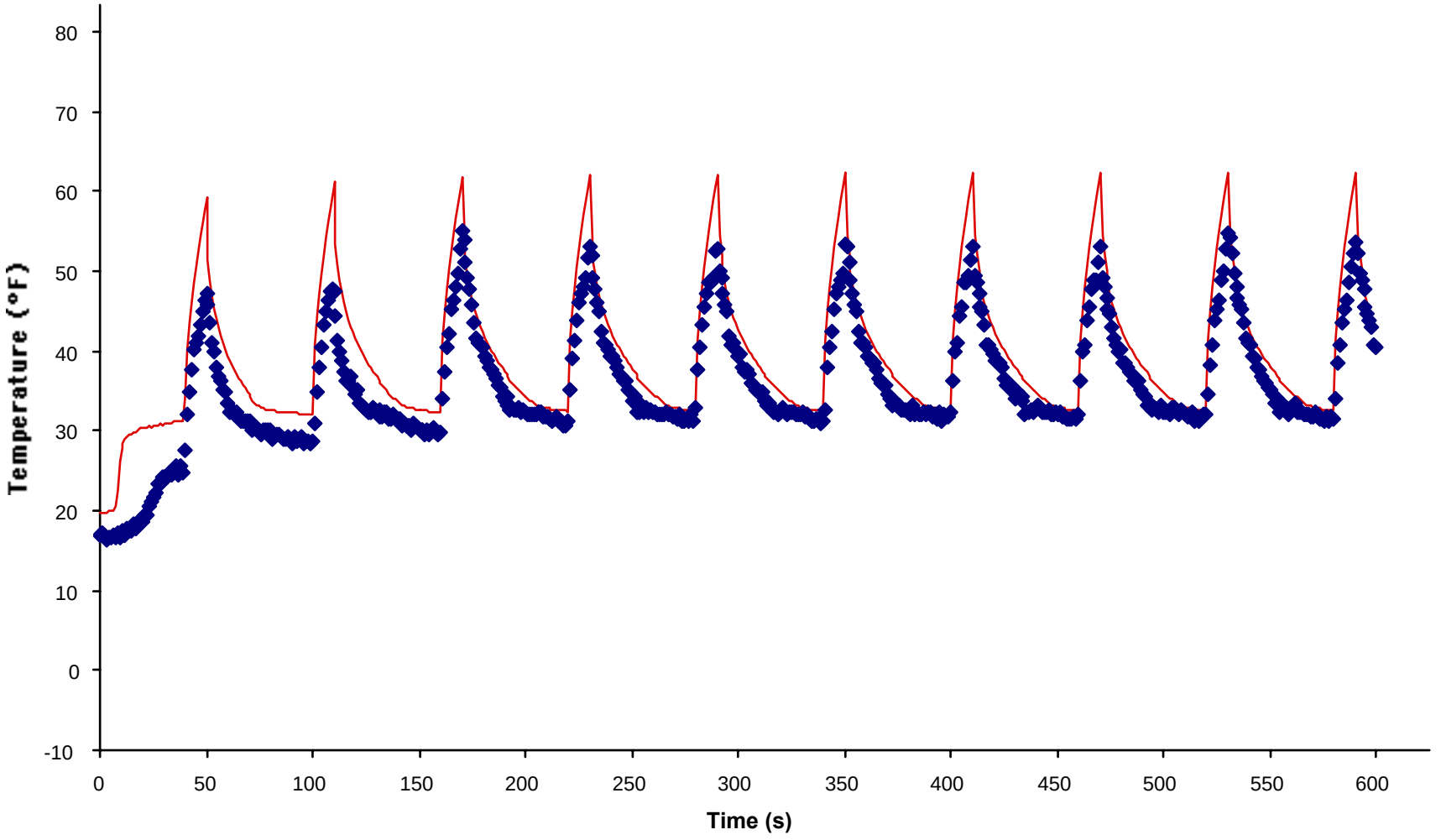


Sample Electrothermal Validation (Laminar)

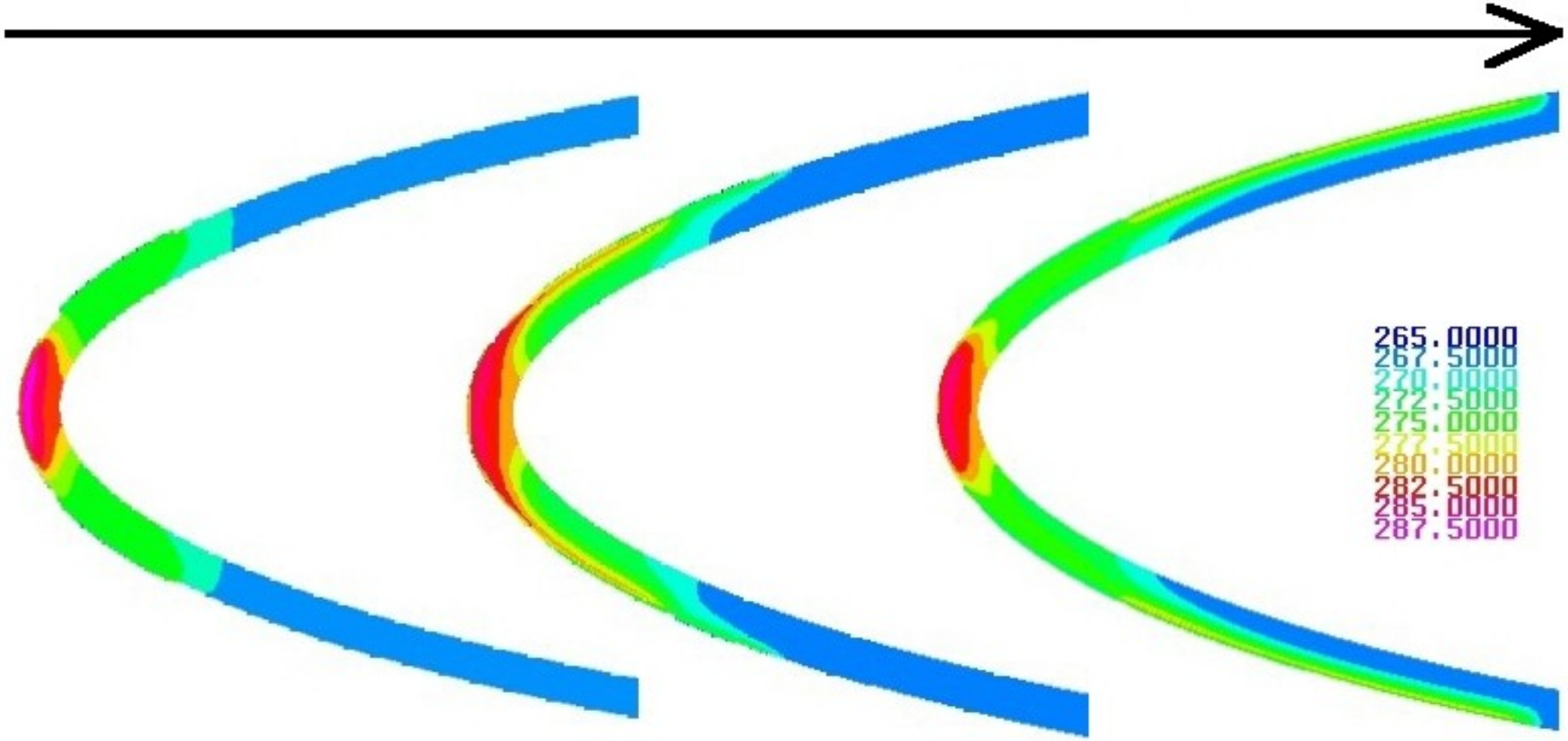


Sample Electrothermal Validation (Laminar)

Run 17 Top, Section B: Heater Temperature



Typical Temperature Progression



Variability of Results

$$absolute\ difference = \left| T_{\exp} - T_{LEW} \right|$$

$$percent\ difference = \left| T_{\exp} - T_{LEW} \right| / (T_{\exp\max} - T_{\exp\min})$$

	% Error	Estimated Error	Avg. % Difference	Avg. Absolute Difference	Avg. % Difference	Avg. Absolute Difference
Mode	Experiment	Experiment	Expert User	Expert User	Untrained User	Untrained User
De-Icing	9%	3 °F	18%	6 °F	35%	11 °F
Anti-Icing	22%	8 °F	45%	16 °F	89%	31 °F
Overall	13%	6 °F	26%	13 °F	51%	25 °F

Quantitative Results

	Laminar, Sectional Shed		Laminar, Nodal Shed		Turbulent, Sectional Shed	
	Avg. % Difference	Avg. Absolute Difference	Avg. % Difference	Avg. Absolute Difference	Avg. % Difference	Avg. Absolute Difference
Overall Deicing	8.6°F	25.7%	9.2°F	29.6%	8.8°F	27.2%
20°F Cases	6.5°F	26.3%	7.3°F	29.6%	5.9°F	22.4%
0°F Cases	11.9°F	24.5%	12.2°F	29.6%	13.2°F	29.0%
Evap. Anti-Icing	35°F	22.7%	55°F	35.6%	88.6°F	56.0%
Running Wet	22.2°F	38.0%	25.6°F	44.2%	33.4°F	53.9%

Ice Shape Results

- **Preliminary Validation of Ice Shape Characteristics**
  - **All cases ran using automated process (not validated)**
- **Insignificant Difference for Most Cases**
  - **All average parameters within 2% of LEWICE 2.0 results**
    - **Majority of parameters < 1%difference from LEWICE 2.0**

Conclusions

- **Bleed Air and Electrothermal Capabilities Available**
- **Electrothermal Validation Performed**
  - **Reasonable (25%) accuracy for deicing or anti-icing applications**
  - **Code results can be calibrated if desired**
- **Additional Data Needed**
  - **Bleed air anti-icers**
  - **Investigate evaporative physics to improve accuracy**